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Water footprint and economic water productivity of sheep meat at farm scale in humid and semi-arid agro-ecological zones

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ABSTRACT

Tunisia is prone to serious depletion of water resources that is threatening the sustainable agriculture development especially the livestock sector. The current study aimed to measure water footprint (WF) and economic water productivity (EWP) of sheep meat within twelve smallholder farms in two different agro-ecological zones in Tunisia; humid in northern and semi-arid in central Tunisia. A year-round monitoring of on-farm practices was performed using water meters and recording equipment's installed in key locations in the target sheep farms. The water source green (rainwater) and blue (from irrigation) corresponds to (i) water used for feed production, (ii) sheep watering, (iii) cleaning and servicing water, (v) water used for crop and pasture yield production, and (iv) economic and production performance. Results show that farms in semi-arid region have the highest WF averaging 9.07 ± 0.48 m^3/ kg sheep body weight (BW) of which 8.58 ± 0.46 m^3/kg BW was green water and 0.49 ± 0.05 m^3/kg BW was blue water. The lowest WF values were recorded in farms in humid region averaging 6.98 ± 0.3 m^3/kg BW out of 6.79 ± 0.27 m^3/kg BW was green water. Around 17.3% of the total WF of sheep meat was attributed to virtual water from off-farm feed production in farms in humid region. However, in farms in the semi-arid region, the proportion of off-farm feed exceeds 65% and they are imported from international markets or produced in northern region. Most of the total volume of water (99%) refers to the WF of feed production. Drinking water, service and cleaning water account only for less than 1%. The assessment of the EWP revealed that farms had an average gross margin per m^3 of water of 0.49 ± 0.1 US $ and US$ 0.29 ± 0.04 in humid and semi-arid regions, respectively. The current results confirm that producing sheep meat in humid region is 20% more efficient in term of water use and create 60% more gross margin return per m^3 of water than in semi-arid region. In addition, semi-arid region is more prone to the impact of climate change that humid region. Moreover, rangeland degradation coupled with the high density of sheep flocks in the semi-arid region, mean that farms in the humid region would profit more from sheep rearing.

1. Introduction

The expanding water scarcity across many countries in the world, mainly in the drylands (e.g. Middle East, North Africa and South Asia countries) is a major constraint affecting the efficiency and threatening the sustainability of production systems. Therefore, water has an important role in the economy of any of these countries. The situation is complicated when the competition for water between men and the major components of these systems, i.e. crops and livestock, is considered (Rijsberman, 2006). Agriculture is by far the largest user of freshwater resources accounting for more than 80% (Molden et al., 2007) of total water. Global livestock production represents about 30% of the global agricultural water requirement, including rain and irrigation water used for food and feed production and withdrawals for livestock husbandry (Mekonnen and Hoekstra, 2012; Ran et al., 2016). The water footprint assessment (WFA) in the agricultural and food sectors have been recognized since few years as a promising indicator of the sustainability of any production system (de Miguel et al., 2015; Pellicer-Martínez and Martínez-Paz, 2016). The water footprint (WF), introduced by Hoekstra and Hung (2002) as a comprehensive indicator of freshwater use, quantifies and maps water consumption and pollution in relation to production or consumption. The WF has three components: Green, blue and grey (Hoekstra et al., 2011). The green WF (rainwater) refers to the consumption of water originated from rainfall that is stored in the root zone of the soil and evaporated, transpired or incorporated by crops. The blue WF (irrigation) refers to the consumption of blue water resources that have been sourced from surface or groundwater resources and is either evaporated, incorporated into a

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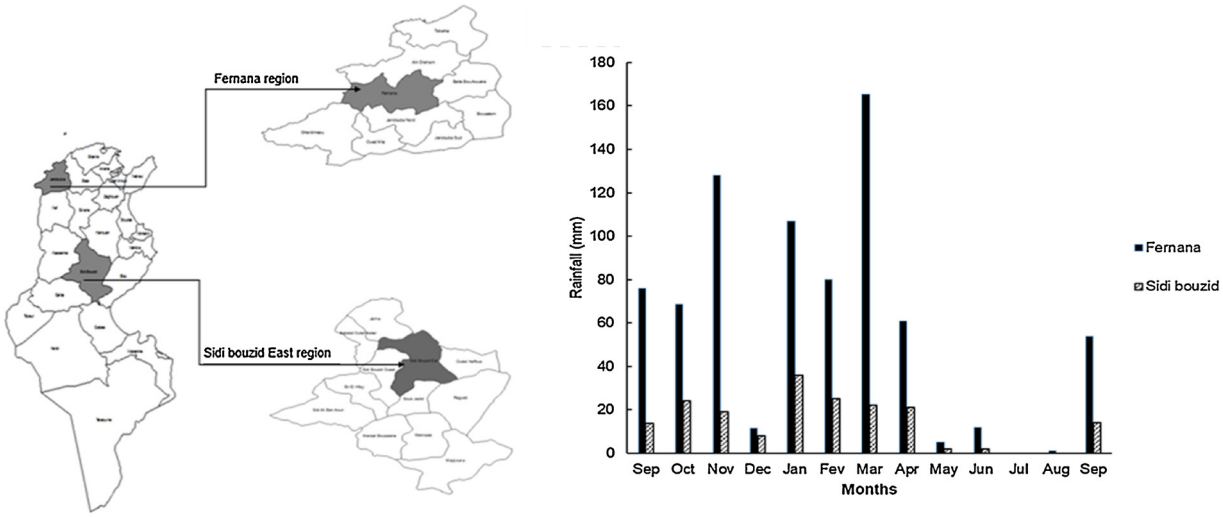

Fig. 1. Geographical location and average monthly rainfall during the period September 2015 to September 2016 of Fernana and Sidi Bouzid regions.

product or taken from one body of water and returned to another, or returned at a different time. The grey WF of a product refers to the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards (Hoekstra et al., 2011). The separation of water sources into green, blue and grey describes different pathways of water use in livestock farming systems. Murphy et al. (2017) reported that the distinction between green and blue WF in sheep farms is useful as it can highlight differences in production systems in term of water use source.

According to Gassert et al. (2013), Tunisia ranked the 33th driest country in the world and is threatened by water scarcity, where the arid and semi-arid areas cover 75% of its total area. Water shortage is a limiting factor for the development of the agri-food production sector. Agriculture sector is by far the biggest consumer of freshwater resources with more than 77% of the available water in Tunisia (Chahed et al., 2008). It is unusual to look at specific water use for any animal product in the Tunisian context although the livestock sector contributes by 40% to the gross value of agricultural production (GIVLAIT, 2016). Freshwater resources dedicated to feed production and animal watering is already limited in Tunisia mainly during dry seasons. Therefore, it is important to gain insight into water consumption of the sheep farming systems in different regions in order to select the least intensive system in terms of water use and to identify mitigation options wherever needed. Based on this, two internationally accepted approaches of WF have been developed: The WF approach as described by Hoekstra et al. (2011) and the Life Cycle Assessment (LCA) as described in the ISO standards. Many studies highlighting the need for high amount of water to produce one kilogram of meat or milk drew the attention of mass media and scientists (Mekonnen and Hoekstra, 2012; Gerbens-Leenes et al., 2013; Bosire et al., 2015; de Miguel et al., 2015; Owusu-Sekyere et al., 2016; Sraïri et al., 2016). However, recent research indicates that these measures could actually lead to higher water consumption due to the intensification of water use and field efficiencies that are far below theoretical values (Batchelor et al., 2014; Owusu-Sekyere et al., 2016; Sraïri et al., 2016). Studies assessing water use in sheep meat production at farm scale are scarce. Toro-Mujica et al. (2016) calculated the WF of sheep meat in central Chile using a simulation-based approach and for evaluating the effects of farm type, management, and rainfall on the WF of sheep grazing systems in a semi-arid environment. In addition, Chatterton et al. (2010) calculated the WF of lamb and beef meats in England using two simulation models (Water simulation model Wasim, and the Cranfield Life Cycle Assessment model). Ibidhi et al. (2017) estimated the WF of sheep meat produced in Tunisia under different farming systems using the Water Footprint Network (WFN) volumetric approach.

Mekonnen and Hoekstra (2012) estimated the WF of various animal products in different production systems, including the grazing, mixed and industrial sheep farming systems, using global averages data such as herd numbers, number of slaughtered animals, yearly animal production and feed intake, derived mainly from FAOSTAT database. Therefore, the current study was performed to fill the gap between literature data and field measurements of the WF of sheep meat. Therefore, the main objectives of this study were i), to determine the WF of sheep production in twelve farms affiliated to humid and semi-arid climates in Tunisia and to identify the components and processes that have the greatest water use in terms of green, blue and virtual water, ii) and to evaluate the economic water productivity of sheep meat in both agro-ecological zones (humid and semi-arid).

2. Materials and methods

2.1. Study locations and farming systems

This study was carried out in two different locations that are home to two different production systems. The first location is in northern Tunisia named Fernana and the second one in central Tunisia and is called Sidi Bouzid (Fig. 1). In twelve representative farms randomly selected, belonging to two different farming systems in the two locations, water use was controlled from December 2015 to September 2016 (Ibidhi et al., 2018). Fernana location is home to the rainfed production system (946 ± 421 mm) (Ibidhi et al., 2018). The average minimum and maximum temperatures are 5 °C and 37 °C, respectively. Cereal cropping and livestock production are the main activities in this farming system where farmers rely on grazing on natural pasture, fallows and cereal stubbles in summer, while in winter season they provide concentrate supplements for their sheep flocks. Livestock is generally watered from public water points (lake, river, and water stagnation). Different conditions prevail in the second location, i.e. Sidi Bouzid. This area is located in central Tunisia which is characterized by a semi-arid climate with an average annual rainfall averaging 217 ± 102 mm and the temperature varies between 15 °C and 39 °C. The low consumable biomass provided by the degraded rangelands is forcing farmers to use high amounts of concentrate supplements, mainly barley and wheat bran. The proportion of concentrate feeds in sheep's diet in central Tunisia, ranges between 40 and 80% while rangeland vegetation's contribution doesn't exceed 15% of the total diet and 5% correspond to agro-industrial by-products (Ben Salem, 2011; Ibidhi et al., 2018). Furthermore, groundwater represents the main

Table 1
Characteristics of the selected sheep farms to monitor water use in humid and semi-arid regions.

	Farms in humid region				Farms in semi-arid region			
Farm structure	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
Farm area (ha)	1.7	0.5	2.5	0.8	2.4	1.5	4.0	1.1
Pasture land (ha)	0.3	0	0.5	0.3	0.2	0.0	1.0	0.4
Cereal land (ha)	1.1	0.5	1.75	0.5	0.3	0.0	0.5	0.2
Oat (ha)	0.3	0	0.5	0.2	0.0	0.0	0.0	0.0
Olive (ha)	0	0	0	0	1.7	0.9	2.7	0.8
Cactus (ha)	0	0	0	0	0.2	0.1	0.3	0.1
Annual rainfall (mm)	742	714	770	30,7	167.6	148.5	186.6	20.9
Herd characteristics								
Number of animals	27	22	33	4.2	38	23	52	11.8
Number of ewes	15	12	18	2.5	20	13	29	6.2
Number of lambs	12	10	15	1.9	17	10	25	5.8
Fertility (%)	92	84.6	94.4	3.7	88.7	80.0	96.2	5.8
Prolificacy (%)	86	73.3	92.3	6.8	94.2	84.2	108.7	10.8
Lamb mortality (% annual)	9	0	21.4	7.1	5.1	0.0	11.5	4.7
Water component								
Water cost (USD $/m^3)	0	0	0	0	0.05	0.04	0.06	0.01

SD: Standard Deviation.

source for sheep watering. The Barbarine sheep is the only breed considered in the selected farms in both regions, since, it is the most important meat breed widespread in Tunisia (Ben Salem et al., 2011). Farms characteristics in humid and semi-arid regions are reported in Table 1.

2.2. Water footprint and economic water productivity of sheep meat concepts

The WF of an animal product is defined as the total volume of freshwater that is consumed and polluted in all processing stages of its production (Hoekstra and Chapagain, 2008). The WF of a live animal consists of different components: the indirect WF of feed production and the direct WF related to the drinking water and service water consumed (Mekonnen and Hoekstra, 2012). The WF of an animal is expressed as:

$$WF_{animal} = WF_{feed} + WF_{drink} + WF_{serv} \quad (1)$$

where, WF_{feed}, WF_{drink}, and WF_{serv} represent the WFs related to feed production, drinking water and service water consumption, respectively. Animal WF is usually expressed as m^3/year/ animal or m^3/animal, when summed over the entire lifespan of the animal. The economic water productivity (EWP) is defined as the value derived per unit of water used, i.e. 'Dollar per drop' (Igbadun et al., 2006; Vazifedoust et al., 2008; Garrido et al., 2010). The EWP of sheep meat was calculated as the gross margin of meat divided by the total amounts of water used, expressed as US$/$m^3$ (Sraïri et al., 2016).

2.3. Experimental design and water use measurement

2.3.1. Experimental design

To investigate the technical water use of lamb production at the farm scale, water meters with continuous flow DLJ models and recording equipment were installed at various points of water withdrawal (irrigation, drinking and servicing water). Water volumes were estimated by frequent measurement determination of discharges from wells and at the entry point of fodder plots irrigated, combined with regular enquiries about the duration of irrigation applications. Furthermore, the protocol consisted of a series of routine visits to farms at times of shifts in management practices, that is, a new cut of fodder crops, a significant change in diets formulation, starting day of irrigation, pasture biomass estimation, etc. Lambs were born in December 2015 and farmers sell them to be slaughtered in the Islamic religious ceremony of mutton scarify (commonly named Eid Al Adha, September 2016). The volume of drinking water was measured when the animals are either in the farm or on the pasture. Water meters are connected on the farm to control drinking water and plastic tanks had a capacity of 70 liters with a line gauge installed near the watering public points or in the pasture. Rainfall data were obtained from the local meteorological station, which was located at a maximum distance of 5 km from farms. Average rainfall data of Fernana and Sidi Bouzid regions from September 2015 to September 2016 are reported in Fig. 1. The rainfall pattern is strongly seasonal in character with a winter rainfall regime and a summer regime in both regions. Rainfall becomes more erratic with great variability from year to year in Tunisia as a result of climate change impacts (Verner, 2013).

2.3.2. Measurement of crop and animal parameters

Forage, pasture and cereal stubbles biomass were determined by weighing plant samples harvested from each plot within a 1 m^2 quadrat at each harvest (Martin et al., 2005). In addition, grassland species in both regions were assessed. The average dry matter (DM) contents of forage crops and pasture was determined by drying biomass samples at 80 °C. Moreover, diet (forage and concentrate) consumed by ewes and growing lambs were recorded and the common diets for both types of farms are presented in Table 2. While pasture intake was determined through sheep behavior monitoring during grazing time. Such monitoring work had been repeated three times by season in all target farms. Sheep behavior in pasture was controlled along 4-day observation period. Total time in the rangeland was apportioned between

Table 2
Typical share of feed ingredients by dry matter for sheep study farms in humid and semi-arid regions.

	Sheep farms in humid farms	Sheep farms in semi-arid region
Feed ingredients (%)		
Concentrate		
Barley	10	20
Commercial concentrate	0	15
Alfalfa pellets	0	5
Fodder crops and hay		
Oat hay	5	15
Wheat straw	5	5
By-products and food waste		
Wheat bran	10	15
Olive leaves	0	2
Rangelands	60	15
Cereal crop-residues	10	2

grazing, walking, drinking water and resting. Five animals from each farm were identified at random. The identified animals in each farm were marked by different colors of paint on their backs. Observations of these animals were made by five observers approximately 30 min after their arrival to the pasture. Generally, all animals grazed together in the morning (7:30 am to 9:00 am) and in the afternoon (3:30 pm to 5:00 pm) in summer and autumn seasons and a unique period of grazing (11:00 am to 16:00 pm) in winter and spring seasons. Four activities were distinguished for controlled animals: (1) grazing, defined as head down whilst searching or consuming herbaceous vegetation, (2) browsing, defined as head down whilst consuming shrubby vegetation, (3) walking, defined as the time when the animal was moving, (4) resting, defined as the period when the animal was immobile, (5) and drinking water. These activities were recorded on the same animal in the morning and in the afternoon. Thus, sets of bites of varying size from the herbage on offer were counted. The combination of bite size and the short-term rate of biting is defined as the instantaneous intake rate, with units reported in g/min. Over the day the animal spends a certain grazing time and the intake during this time was calculated following equation 2 (Gordon, 1994):

$$\text{Daily Intake} = \text{Bite weight} \times \text{Bite rate} \times \text{Grazing time} \quad (2)$$

Furthermore, fertility, prolificacy and lamb mortality rates were determined. The fertility was defined as the ratio of pregnant ewes to mated ewes, and prolificacy as the ratio of lambs born to ewes mated.

2.3.3. Water footprint and economic water productivity measurement

The WF of a growing crop is the sum of the process water footprints of the different sources of water:

$$WF_{crop} = WF_{green} + WF_{blue} \quad (\text{volume/mass}) \quad (3)$$

where, WF_{green} of crop is the total volume of rainwater that evaporates from the field during the same period. While, the WF_{blue} refers to the total amount of irrigated water that evaporates from the field over the total length of the crop's growing period (Hoekstra et al., 2011). The WF_{green} (m^3/ton) is calculated as the green component in crop water use (CWU_{green}, m^3/ha), divided by the crop yield (Y, ton/ha) (Eq. (4)). Similarly, the WF_{blue} (m^3/ton) is calculated as the blue component in crop water use (CWU_{blue}, m^3/ha), divided by the crop yield (Y, ton/ha) (Eq. (4)):

$$WF_{green} = \frac{CWU_{green}}{Y} \quad (\text{volume/mass}) \quad (4)$$

$$WF_{blue} = \frac{CWU_{blue}}{Y} \quad (\text{volume/mass}) \quad (5)$$

The Aqua crop model developed by the Food and Agriculture Organization (FAO) was used to compute the green and blue crop water use (CWU, m^3/ha), which is the sum of the daily evapotranspiration (ET, mm/day) over the complete growing period of the crop:

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green} \quad (\text{volume/area}) \quad (6)$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue} \quad (\text{volume/area}) \quad (7)$$

ET_{blue} and ET_{green} represent the blue and green water evapotranspiration, respectively. The water depths are converted from millimeters to volumes per area (m^3/ha) by using the factor 10. Summation is done over the complete length of the growing period (lgp) from day one to the harvest (Hoekstra et al., 2011). To calculate the WF of cereal crop-residues, wheat bran and olive leaves, crop WF was reallocated over the crop residues or agro-industrial by-products and the crop yields using the weight and value fractions, then distributed the WF to the grains and to the crop-residues/by-products according to their yield (product fraction *fp*) and economic value (value fraction *fv*) (Ibidhi et al., 2017). In addition, the use of off-farm feed such as purchased feed represents 'virtual water' (Allan, 1998). The equivalent virtual water corresponding to off-farm feed resources (mainly cereal grains, alfalfa pellets and wheat bread) was obtained from Hoekstra and Chapagain (2007). The economic return from meat sales was calculated for each farm. Gross margins for body weight gain (BWG) were determined as the difference between the incomes and the expenses related to feed production and veterinary treatments, as well as of farmworkers' wages, and without wages for family members' (Sraïri al., 2016). The economic value of BWG was estimated from market prices in both study locations: US $ 5 /kg BW (the exchange rate in the 12th January 2016: 1 US $ = 2.198 Tunisian Dinar). The WF was calculated for BWG (m^3/kg BW). Then, the EWP of BWG was calculated as the gross margin for BW of meat divided by the total amounts of water used, expressed as US $/$m^3$.

3. Results

3.1. Water use monitoring of crop production

The WF of cereal crop residues, wheat bran, wheat straw and olive leaves are presented in Table 3. Water volumes assigned to crop production varied widely among farms and region and were largely determined by the amount of rainfall and irrigation practices. Table 4 shows the volume of water consumed by each crop, water origin (green or blue) and the yield expressed as kg DM/ha in both farms in humid and semi-arid regions. Results show that crops and pasture production in farms in humid region are cultivated predominantly from green water resources. While in semi-arid region, farmers rely on blue water resources for irrigation. In farms in humid climate, the cereal land was cultivated with rain-fed wheat and barley, where the cereal stubbles represent an added value for livestock in summer. Oat (*Avena sativa*) is also cropped for fodder production, grown in four farms for hay production. Pasture is a key component of sheep feeding in the six experimental farms in humid region. Pasture biomass yield ranged between 7030 and 8880 kg DM/ha and exceeds that of the pasture in the semi-arid region (Table 4). Among the farms in semi-arid region, only four farms cropped barley and blue water made up 60% of the water demand in barley production. Rangelands in farms in semi-arid zone are prone to degradation and their consumable biomass yield ranged between 1495 and 2100 kg DM/ha (Table 4).

3.2. Drinking and servicing water monitoring

The result of monitoring drinking, servicing and cleaning water and the average daily water intake of the sheep flock in farms located in humid and semi-arid regions are presented in Table 5. The average total drinking water in the humid and semi-arid farms was 26.2 and 47 m^3,

Table 3
Water footprint of crop yields, crop residues and by-products with and without allocation.

Crop residues/by-products	Crop origin	Production fraction (fp)	Value fraction (fv)	Without allocation	With allocation
				WF crop yield (m^3/ton)	WF crop residue/ by-products (m^3/ton)
Cereal crop residues	Wheat	0.12	0.03	1900	475
	Barley	0.10	0.03	3090	927
Olive leaves	Olive trees	0.35	0.02	10253	586
Wheat bran	Wheat	0.17	0.15	1827	1612
Wheat straw	Wheat	0.50	0.15	1827	548

WF : Water footprint.

Table 4
Crop water use (m^3/ha), yield (Kg DM/ha) and water footprint (m^3/kg of DM) of crops production in the selected farms in humid and semi-arid regions.

Crop	Sheep farms in humid region				Sheep farms in semi-arid region			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
Barley								
CWU green (m^3/ha)	5103	4981	5210	116	1324	1313	1350	18
CWU blue (m^3/ha)	0	0	0	0	3600	3250	4000	324
Yield (Kg DM/ha)	1650	1500	1850	132	1183	1100	1220	57
WF (m^3/kg of DM)	3.09	2.82	3.34	0.22	4.16	3.74	4.83	0.45
Wheat								
CWU green (m^3/ha)	5455	5170	5580	155	–	–	–	–
Yield (Kg DM/ha)	2363	1530	2750	443	–	–	–	–
WF(m^3/kg of DM)	2.31	1.92	3.57	0.60	–	–	–	–
Oat								
CWU green (m^3/ha)	4993	4860	5110	104	–	–	–	–
Yield (Kg DM/ha)	1563	1400	1700	125	–	–	–	–
WF (m^3/kg of DM)	3.20	2.1	3.70	0.31	–	–	–	–
Pasture								
CWU green (m^3/ha)	5825	5669	5980	170	1178	1210	1720	279
Yield (Kg DM/ha)	8193	7030	8880	721	1128	1190	1600	225
WF (m^3/kg of DM)	0.71	0.64	0.85	0.09	1.04	1.02	1.08	0.03
Chopped cactus								
Green CWU (m^3/ha)	–	–	–	–	1603	1485	1720	129
Yield (Kg DM/ha)	–	–	–	–	8629	8100	9300	478
WF (m^3/kg DM)	–	–	–	–	0.19	0.16	0.20	0.01

CWU: Crop water use; SD: Standard Deviation.

respectively. By animal, farms in semi-arid climate exhibit a higher drinking water amount both in ewes and lambs than in farms in humid region. Drinking, servicing and cleaning water represent only 1% of the total water use of the production of one kg of meat, and it is two times higher in farms located in the humid area than in those hosted in semi-arid region. The amount of water that an animal consumes as a drinking and cleaning water during its lifetime is negligible compared to water requirements for feed production.

3.3. Water footprint and economic water productivity of sheep meat

Total off-farms feed intake DM (%), production and economic lamb performance in farms in humid and semi-arid regions are showed in Table 6. The EWP and the WF of one kg of sheep meat including water used for feed production, drinking water, servicing and cleaning water are presented in Table 7. The average total volumetric WF of the six farms in humid zone was 6.96 m^3/kg BW (range from 6.5 to 7.32 m^3/kg BW). The green water input into the sheep systems represents 97.5% of the WF meaning that the blue water represents only 2.5%. On average 17.3% of the total WF of sheep meat correspond to virtual water from off-farm feed production (Table 7). While, the average total volumetric WF of the six sheep farms in semi-arid zone was 9.07 m^3/kg BW, (range from 8.42 to 9.80 m^3/kg BW). The green water contribution to the sheep meat production represents 95% of the total WF. An average of 65% of the total WF of sheep meat was attributed to virtual water from off-farm feed production. Most of the total volume of water (99%) refers to the WF of feed production. The assessment of the economic value of water productivity of BWG agreed with the results for water volumes used and gross margins achieved. In all farms, the water used to grow lambs creates a positive gross margin. Farms had an average gross margin per m^3 of water of 0.49 and US $ 0.29 in humid and semi-arid regions, respectively.

4. Discussion

The current study highlighted the water use of sheep meat in twelve smallholder farms located in two different agro-ecological regions (humid and semi-arid) of Tunisia. The total volumetric WF for the sheep study farms was 8.02 m^3/ kg BW. Similar finding was reported by Ocak et al. (2013) in Turkey and Murphy et al. (2017) who assessed the volumetric WF of sheep meat in six farms in Ireland. The later authors found that the WF of sheep farms accounts 7672 l/kg carcass weight (CW) of which 7635 l/kg CW was green water and 37 l/kg CW was blue water. The WF allocated to the production of pasture and concentrate contributed by 87% and 12% to the total WF of sheep meat, respectively while the on-farm water use represents 1% of the WF. In contrast, this amount of water needed to produce one kg of BW corresponds to half of that reported in a previous study by Ibidhi et al. (2017) on the determination of WF of sheep meat produced in Tunisia during the period 1996-2005. The difference could be explained by the fact that

Table 5
Drinking and servicing water monitoring of sheep flock in farms in humid and semi-arid regions.

Farm	Farms in humid region				Farms in semi-arid region			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
Drinking water (m^3/year)	26.2	20.7	33.9	4.7	47	259	67	16.7
Average drinking water (l/day)								
Ewes	4.4	3.8	4.6	0.3	5.6	5.3	6.1	0.3
Lambs	2.8	2.5	3.4	0.3	4	3.4	4.6	0.5
Servicing and cleaning water (m^3/year)	4.5	1.8	5.7	1.4	9.8	4.2	14.4	4.0
Average servicing and cleaning water (l/day)								
Ewes	1	0.5	1.2	0.3	1.6	1.2	2.0	0.3
Lambs	0.5	0	1.1	0.4	1.1	0.3	1.3	0.4

SD: Standard Deviation.

Table 6
Total feed intake in and off farms, production and economic lamb performance in farms in humid and semi-arid regions.

	Farms in humid region				Farms in semi-arid region			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
Total feed intake (kg DM/year)	8531	1190	12950	4013	13644	8724	19271	4200
Total off-farm feed uses DM (%)	23	14	48	12.6	77	72	85	4.7
Average BW gain (kg/ production cycle)	24.7	23	26	1	32	30	34	1.4
Meat profitability (US $/kg of BW)	3.4	2.8	4.0	0.4	2.6	2.3	2,9	0.3

BWG: Body weight gain; BW: Body weight; SD: Standard Deviation.

the assessment performed by the later authors is based on Mekonnen and Hoekstra (2012) database and it is adapted to the Tunisian sheep farming systems in the period 1996–2005. Furthermore, this study is an updated field case study on WF of sheep farming in Tunisia. In addition, the amount of water found in the current study is 23% lower than that reported by Mekonnen and Hoekstra (2010) (10,412 l/kg sheep meat) and seven times lower than results obtained by Chatterton et al. (2010) on English lambs (57,800 l/kg of carcass weight), respectively. Producing sheep meat in humid climate required 20% less water per kg of BW than in semi-arid climate. This finding is explained by two main reasons. First, the WF of sheep meat is highly correlated with feed production since in the semi-arid region farmers relied on concentrate feeds (40%). While in humid region, they relied on grazing (60%). Concentrate feeds show a higher WF compared to rangelands and fodder crops, which had an impact on the total WF of sheep meat. Second, the imbalance of rainfall between the two regions and the inefficiency of irrigation in converting to feed biomass is another reason for the difference of the WF values between the two kinds of farms.

Mekonnen and Hoekstra (2010) assessed the WF of sheep meat across three standard farming systems (grazing, mixed and industrial) in many countries. They came up with the conclusion that water use of livestock products depends on farming systems and farmers' practices. The monitored WF values in the present study differ from earlier studies but are still within the same ranges. The WF of sheep meat recorded in the current study averaged 6.98 and 9.01 m^3/kg BW in farms in humid and semi-arid regions, respectively. In farms located in both humid and semi-arid regions, feed production is the largest consumer of freshwater (more than 99%) for sheep meat production. This finding is in line with the results reported by many authors (Mekonnen and Hoekstra, 2010; Toro-Mujica et al., 2016; Ibidhi et al., 2017). WFs for drinking and servicing of sheep production in both categories of farms are negligible and similar to those published by Mekonnen and Hoekstra (2010). The main reason of such variation of the WF of sheep meat in the selected farms refers to diet composition and rainfall levels across the agro-ecological zones. In the farms located in humid zone, farmers offer to their sheep flocks diets composed of on-farm produced feedstuffs except for wheat bran. Grazing on natural rangelands is a key factor of the final WF of sheep meat. Fodder crops, cereals and pasture are fully rain-fed. Cereal crops (i.e. barley and wheat) are for dual-purpose uses: Grains for human's consumption and cereal straw and stubble for sheep grazing mainly during the summer season. Cereal crops in farms in the semi-arid region were low compared to those produced in the humid region. This difference in yield production could be explained by the inefficiency in irrigation in farms in the semi-arid region. However, surface water and groundwater include only water for drinking and servicing. Therefore, the largest contributor to the WF of meat was green WF averaging a contribution rate of 97.5%, this reflects the importance of rain-fed agriculture as a source of feed in livestock production systems. These percentages are consistent with the results obtained by Ibidhi et al. (2017) in the agro-pastoral system in Northern Tunisia where grazing on cereal stubbles is a common practice. In farms located in the semi-arid region, more than 65% of the WF of sheep feeds are outsourced, in general, purchased from international markets or from the northern region in Tunisia. Rangeland in the semi-arid region is degraded. Therefore, the contribution of range vegetation in sheep diets is low. Chopped Spineless cactus (*Opuntia ficus indica f. inermis*) is a drought tolerant plant species and easy to grow under harsh conditions. In addition, its chopped cladodes are fodder source for sheep feeding. It serves to reduce drinking water since the cladodes of this plant are extremely high in moisture (90–95%). Beside the biophysical processes related to water use of sheep production at farm scale, the current analysis focused on the economic aspects. All farms achieved positive economic results in BWG. The gross margin is higher in farms in humid region than in farms in semi-arid region. Two main reasons could explain such difference: i) all feed ingredients in humid farms were produced at the farm level, while the farmers in semi-arid zone relied on purchased feed including concentrate feeds (e.g. barley, wheat bran, etc.) and roughage (e.g. hay and straw), ii) in farms exposed to semi-arid climate, irrigation of some crops and fruit trees (e.g. barley, olive trees, etc.) is a common practice that is imposed by the problem of rainfall scarcity. The current study is, to the best of our knowledge, the first assessing the EWP of sheep meat. The EWP per kg of sheep meat in farms in humid region was 60% higher than in farms in semi-arid region. Sraïri et al. (2016) calculated the irrigation EWP per kilogram of BWG in five dairy farms in Morocco and came up with an average value of US $1.39/$m^3$. The current study showed that sheep meat production

Table 7
The volumetric water footprint (m^3/kg BW) according to water source (green and blue) and production components, % of virtual water and economic water productivity (US$/$m^3$) of sheep meat in farms in humid and semi-arid regions.

Farm	Farms in humid region				Farms in semi-arid region			
	Average	Minimum	Maximum	SD	Average	Minimum	Maximum	SD
WF of feed production (m^3/kg DM)	6.93	6.46	7.27	0.30	9.01	8.36	9.75	0.48
WF of drinking water (m^3/kg BW)	0.04	0.03	0.04	0.002	0.04	0.04	0.05	0.002
WF of servicing and cleaning water (m^3/kg BW)	0.008	0.004	0.01	0.003	0.01	0.006	0.01	0.002
WF total (m^3/kg BW)	6.98	6.5	7.32	0.3	9.07	8.42	9.80	0.48
WF green (m^3/kg BW)	6.79	6.40	7.14	0.27	8.58	8.00	9.31	0.46
WF blue (m^3/kg BW)	0.19	0.10	0.36	0.09	0.49	0.42	0.56	0.05
% of virtual water	17.3	4	41	13	65.5	58	70.3	5
EWP (US $/$m^3$)	0.5	0.4	0.6	0.1	0.3	0.2	0.3	0.04

BW: Body weight; EWP: Economic water productivity; SD: Standard Deviation; WF: Water footprint.

in the rain-fed farming system is more water productive from an economic perspective versus sheep meat produced in the semi-arid system in central Tunisia.

It is clear from this study that irrigation in farms located in the semi-arid region is not efficient (wastage of water, traditional technology) since water is not efficiently converted to fodder biomass production and therefore to sheep meat production. This would have a drastic impact on groundwater availability and would in this case exacerbate water scarcity in this region. Moreover, this study showed that many farms in both humid and semi-arid regions are characterized by a low animal performance which is ascribed to several factors: High mortality rate which averaged 9% in farms with the humid climate, low fertility and reproduction failure, and the unbalanced diets due to the lack of a protein source. All these factors affect livestock productivity and the WF of sheep meat production. Furthermore, the current research work had been conducted along a dry year (Ibidhi et al., 2018). Therefore, simulation scenarios of various types of years (dry, normal and wet) should be emphasized to assess the impact on the WF of sheep meat.

Different interventions could be adopted to reduce WF and increase EWP of sheep meat production. Many authors had confirmed that feed production is the most water demanding activity at the farm level (Gerbens-Leenes et al., 2013; Owusu-Sekyere et al., 2016; Sraïri et al., 2016). In farms located in both humid and semi-arid regions, the WF of sheep meat is highly correlated with WF of feed production. Farmers should use feed ingredients with low-WF in order to reduce the final WF of animal (Descheemaeker et al., 2010). In farms in the humid region, cereal crop-residues mainly stubbles are an important feed source for sheep in the summer season. Cereal crop-residues have a low WF (0.48 and 0.93 m^3/ kg of wheat and barley residues, respectively). Therefore, grazing on cereal crop-residues could be considered as an option to improve water use efficiency for sheep production, which will have a lower impact on the total WF of sheep meat. Pasture vegetation is a key diet component in humid region. While, in the semi-arid region, rangeland rehabilitation through fodder shrub and cactus plantation and grazing habits management could be another option to increase biomass production and to provide alternative energy and water source to improve carcass yield and enhance feed conversion efficiency (Neffar et al., 2013; Sivakumar et al., 2013). This environment-friendly option could reduce water depletion (Bosire et al., 2015). Rainwater harvesting could be an effective solution to overcome water shortage during dry seasons. In farms exposed to semi-arid climate, virtual water clearly has a larger contribution in the WF of meat. Decision to use virtual water should be based on the green and blue WF of feed ingredients produced at the farm level (e.g. barley) to reduce the pressure on limited blue water resources in this region. The transportation of animal feeds from northern (water-rich part) to central and southern regions of Tunisia (water-poor regions) could be achieved through the export of water in virtual form. Such form could be used as an alternative to improve national water use efficiency of the livestock sector and to achieve water security in water-poor regions in Tunisia. Feed shortage in semi-arid region is associated with an important use of concentrate feeds in livestock diets. Mekonnen and Hoekstra (2012) assumed that the WF per kg of concentrate feed is generally higher than that of roughages. Therefore, the use of cost-effective alternative feed sources characterized by high water use efficiency like cactus (cladodes) and olive trees (foliage) should be targeted. In the current study, two types of water for sheep meat production were accounted. Further investigation is needed to measure the grey WF of sheep meat at the farm level.

The WF can be used as an indicator of freshwater use and it can be an informative indicator for policy and decision makers (Steen-Olsen et al., 2012; Rushforth et al., 2013; Hoekstra, 2014; Huang et al., 2015; Ibidhi et al., 2017). The findings reported herein should be considered as good tools for policy makers to support sheep farming system in rainfed regions. In addition, a benchmarking of the WF of sheep meat through the extension of WF assessment to other farming systems and other regions exposed to climate change impacts and water scarcity that is, for example, prevailing in southern Tunisia is highly relevant for the national water policy development. In addition, improving sheep productivity is also a key driver to enhance the efficiency of water use mainly in semi-arid and arid regions. Furthermore, increasing the EWP is an important element for the sustainability of sheep farming in both humid and semi-arid regions, on-farm interventions measures can be achieved through monitoring irrigation water volumes applied on crops mainly in farms in semi-arid region, assessing diets' nutrients contents to avoid losses and following the components of sheep productivity (i.e. fertility, prolificacy rates, mortality rates and feed conversion efficiency) (Descheemaeker et al., 2011).

5. Conclusion

To the best of our knowledge, the current study is the first assessing water use of sheep meat at farm scale through year-round monitoring of on-farm practices. The average WF of sheep meat recorded in the present study is 6.98 and 9.01 m^3/kg BW in farms located in humid and semi-arid regions, respectively. The average EWP per kg of sheep meat in farms exposed to humid climate was 60% higher than in those located in the semi-arid region. Feed production is a hotspot in term of water uses in both categories of farms. Green WF is the main water component of the total WF of sheep meat in farms in humid region. However, under the semi-arid climate, farmers rely on virtual water. In brief, the production of sheep meat under the rainfall farming system in northern Tunisia is less intensive in term of water use and generates more economic benefit per drop of water than in the semi-arid farming system in central Tunisia. Changing production systems practices to make meat production more efficient and productive in term of water use particularly in dry countries would be the future production scenario for increasing meat production and enhancing food and water security.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.smallrumres.2018.06.003.

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